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COMMON TIME REFERENCE FOR INTERIOR BALLISTIC DATA

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The world of interior ballistics has long been confronted with the lack of consistent time reference points. The ballistic process has no clearly defined zero time point and no clear measure of the length of the pressure pulse. The normal ballistic plot usually has a rather clear peak pressure, but without a clear zero the time-to-peak is an elusive concept. This work will demonstrate the use of mathematical functions to establish a consistent time reference zero time and a well-defined time-to-peak or time constant. These two parameters can then be combined with the nominal peak pressure, to produce nondimensional ballistic data.

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INTRODUCTION

In mid-1993 a small program was started to set up a gun heating bench mark experiment for a high performance 155-mm cannon. The data set included temperature data for five rounds fired in a prototype 52 caliber howitzer during June 1991. In this experiment, the time base started (time = 0.0) at the closing of the firing circuit and the actual ballistic pulse was recorded some 70 to 90 milliseconds later. The thermal analysis was based on interior ballistic information calculated using the XNOVAKTC code (refs 1,2) in which the ignition process starts from an "Ignitor Discharge Function" and results in a 5 or 6 millisecond delay. This makes it rather difficult to plot the experimental and analytical data on a common time base without some form of manual shifting of the time axes for the different data sets. It seemed that a more direct method of calculating a reference time would be helpful.

This dilemma was helped by an old observation. Approximate interior ballistic information can be generated by splining a haversine function with a decreasing exponential function. This method requires three conditions on the junction between the two functions:

1. The junction is to the right the of peak of the haversine.
2. The two functions are continuous.
3. The slope is continuous at the junction.

Using this method of approximating an interior ballistic pulse requires only three reference points from the ballistic data, zero time, one at the peak pressure, and another near shot ejection.

It became apparent that a consistent time reference could be established by fitting this dual function approximation to any interior ballistic pressure data and using the zero of the haversine as a reference or "delay time." This time could be used as a reference point for plotting and would allow direct comparisons with other data. The required fitting procedure was available in a program (XNBASE) used to evaluate XNOVAKTC solutions. In this case, it was being used to evaluate the approximate ignition delay time for different ignitor discharge functions. The method was then moved to a smaller program (TDELAY) for evaluation of any interior ballistic pressure-time data. This new application suggested some changes to improve accuracy and insure more robust operation when used with data from different sources.

As the work progressed, it became apparent that the method may be useful for the evaluation of data from the a wide variety of gun firing data including liquid propellant (LP) gun pressures. The LP data sets are very complex with many large pressure oscillations that

add another numeric problem. The nominal pressure peak is masked by the oscillation behavior, and it therefore becomes necessary to add a high level smoothing method to accommodate this problem.

SPLINE FUNCTION APPROXIMATION

This method is based on the notion that a ballistic function can be approximated by the piecewise application of two analytic functions. First is the haversine

$$f(t) = a * SIN(b*t)^2 \tag{1}$$

This function has an initial slope of zero and rises smoothly to a peak, as do ideal interior ballistic curves. It is shown in Figure 1 and approximates interior ballistics, which are dominated by stable burning of propellant grains. The second function is a simple decreasing exponential

$$f(t) = a * e^{-b*t} \tag{2}$$

This is also shown in Figure 1 and approximates the ballistics, which are dominated by the adiabatic expansion and blowdown processes.

Figure 2 shows an approximate ballistic pulse and the points that are required to totally define it. The points P0, P1, P2, and P3, are defined at time and pressure coordinates (t0,P0), (t1,P1), (t2,P2), and (t3,P3). The haversine starts with the zero point P0 and is defined by a single value at the peak pressure point P1. The exponential function also requires two more points for its definition, one point near shot ejection of the gun P2 and a second P3 at the junction of the two functions. This junction point is selected to be first order continuous. That is, the values of the two functions and the first derivatives are equal at this point.

A major advantage of this method is that only three key data points are required to define the spline function, zero time P0, P1, and P2. The last point is calculated from the other three. As will be shown later, the time difference between points P0 and P1 (t1 - t0) or rise time can be considered a "time constant" for the ballistic curve. Also, the maximum pressure P1 can be considered a reference pressure. The time constant and reference pressure can be used to normalize any ballistic curve.

FITTING ALGORITHM

The original curve-fitting algorithm was chosen because it was readily available and seemed to work well. It was not an optimal method and further work was necessary for a more general and robust method. In any case, the method is a simple search for the starting

point of the haversine function that will have the lowest RMS error when compared to the ballistic data. This time then becomes the required delay time. The following steps are required:

1. From the data select a key point at maximum pressure (P1).

2. Select a second key point near shot ejection (P2).

3. Select a time to start a single direction search for P0.

4. Calculate a series of approximate ballistic curves spaced between the starting time t0 and the time t1.

5. Calculate the RMS errors for each of these curves.

6. The minimum RMS error defines the best fitting curve.

7. t0 for the best fit curve is the reference or delay time.

8. The difference between the delay time and the time for the peak pressure (t1) is the time constant or rise time.

This method seems to favor the fitting of the haversine function, which may be the only one that is necessary. However, inclusion of the exponential seems to insure the monotonic decrease in the RMS error until the optimal delay time is found. Results of such an analysis are shown in Figure 3 for experimental data from the 155-mm howitzer test (ref 3). In this case, the data set was initially smoothed to help remove small data errors. The figure shows three plots: the original data, the smoothed data, and the spline function approximation. Note that the smoothing has no visible effect on the experimental curve and is probably unnecessary for this data set.

The addition of LP gun pressure oscillations adds a great deal of complexity to the problem. In this case, the large pressure oscillations mask the position of the initial points P1 and P2 and the data must be smoothed before these points can be selected. A positive kernel (PK) smoothing method was obtained from Mr R. Soanes (ref 4) and seems to produce excellent results. PK smoothing is a linear, shape-preserving method that is explained in Reference 4; however, in this case only a single pass is used. The smoothing then provides a reasonable curve fit that can be used to do an initial selection of the key points P1 and P2 and a trial spline function can subsequently be selected.

Using results of the trial solution, a corrected set of key points can be calculated using a local fit of two least squares parabolas. The first is a local fit in the region of the peak

pressure point P1. In this case, the maximum point of the parabola is selected as the new key point. In the case of the second key point P2, the original time is kept and a new pressure is calculated from the second local parabola.

RESULTS

To be of value, a method like the one reported here must be shown to be useful, and must also show a reasonable level of reliably in producing the desired result. Because this is an empirical algorithm, the reliability of the method cannot be demonstrated in a rigorous mathematical sense, but must be demonstrated through a series of examples. These examples show data from several sources and a wide range of gun systems. The data will be shifted in time to place all data, in a particular plot, on the same time base.

The first is the original example that started the work and is shown in Figure 4. This figure shows seven plots, two of which are XNOVAKTC interior ballistic simulations and the other five are from the bench mark experiment. They are all shown on the time base of the Benet Laboratories solution with the calculated delay times and correction factors shown in Table 1. When the data sets are plotted in this way, the differences in the seven data sets can easily be seen. The two solutions are very close together, which was the desired result. The five experimental curves are again very closely bunched, but the required time corrections show a major variation in the process that ignites the propellent bed.

Table 1. 155-mm Bench Mark Delay Times and Plotting Corrections

Case	Delay Time (ms)	Correction (ms)
Benet Solution	5.33	0.0
Dover Shot 37	76.55	71.22
Dover Shot 38	71.75	66.42
Dover Shot 39	84.20	78.87
Dover Shot 40	70.65	65.32
Dover Shot 41	71.45	66.12
ARL Solution	5.66	0.33

At this point a second parameter may be introduced, which is the time constant of the ballistic process. It is the rise time of the haversine and may be used as "characteristic time" for generating a normalized time base plot. If the peak pressure (P1) is used as a

"characteristic pressure" for normalizing the height, fully normalized plots can be generated. Figures 5 and 6 show calculated pressure-time curves for ten different ammunition systems in five different guns. These guns vary from 25-mm to 155-mm bore diameter and have a wide range of pressures and time constants. The curves have been split into two figures for greater clarity and two curves were repeated to aid in the comparison. Table 2 is a summary of gun systems and original time constants and peak pressures.

Table 2. Definition of Solutions with Pressure and Time Constants

Ammunition System	Gun Bore and Type	Maximum Pressure (MPa)	Time Constant (s)
M833	105-mm Tank Gun M68	454	0.002685
M900	105-mm Tank Gun M68	497	0.003099
M203	155-mm Test Howitzer	264	0.007737
M829	120-mm Tank Gun M256	515	0.002553
M829A1	120-mm Tank Gun M256	510	0.002939
M829A1(hot)	120-mm Tank Gun M256	659	0.002261
M791	25-mm Machine Gun M242	489	0.000568
M919	25-mm Machine Gun M242	492	0.000586
AMGS	25-mm Erosion Test Gun	452	0.000891
N76mm	76-mm Naval Gun	504	0.003911

An inspection of Table 2 shows the variation in the original pressure-time data plotted, however, the normalized data demonstrates the similarity in the overall quality of the curves. There are two exceptions. The first is the M900 solution where the transition from normal burning to adiabatic expansion happens very close to the maximum pressure point. This produces an abnormally sharp peak that is not well represented by the total algorithm. The second prominent feature of these plots is the fact that the 25-mm data (M791 and AMGS) tend to be much wider and the curves fall to the right of the other data. This may relate to the fact that the smaller machine gun barrels are relatively longer than the larger cannon barrels.

The last example is that of an experimental pressure-time curve from a regenerative liquid propellant gun (RLPG) firing (ref 5) and was selected because of its unusually protracted ignition phase. This feature itself could be a problem for data analysis, however, the data are also very complex with large pressure oscillations. This type behavior requires

the initial smoothing in order to find the two key data points. The smoothing was done by using PK smoothing, and the results are shown in Figure 7 as a fully normalized plot. This smoothing process is only used as an aid in the selection of the two key data points P1 and P2. The actual spline-fitting process is done with the original data and these results are shown in Figure 8, which shows the final fitted function. In this example, the fitting procedure has ignored the protracted ignition phase and shown something of the fundamental pressure-time data.

DISCUSSION

Clearly, the curve-fitting method reported here will work for analytically-derived data and experimental data of poor quality. However, the primary concept is the simple idea of using a standard function set as a basis for calculating some generic properties of various ballistic pressure versus time curves. In this work the peak pressures at point P1 and the second point P2 were simply selected from the available data. This process has two problems, the first one is that the true peak pressure may be hidden in a complex response that requires some extra processing. The second problem is that the algorithm will not process all data and produce high quality results.

Figure 4 demonstrates the power of this method to provide reference times. The method is based on a curve fit rather than a single point defined by arbitrary rules. Further, the curve fit tends to favor the entire leading pressure rise of the pressure data. The legend box recaps the calculated time corrections for the seven curves (in milliseconds). The strong variation in the different experimental values serves to demonstrate a fundamental variation of the firing process. This has long been a problem when evaluating experimental data. There is also a rather definite difference in the two numeric calculations. However, this method allows direct comparison of all the various curves.

Figures 5 and 6 allow direct comparison of ballistic information from a wide variety of gun and ammunition types. The M900 curve is repeated on both because it is a prominent curve and provides the first common reference. The M791 curve does the same thing in that it clearly falls to the right of the other data. These calculated curves are plotted from approximately 280 data points at nonuniform time intervals. The individual points are skewed to the left for greater definition of the curve, during the in-bore phase, before shot ejection. The smooth behavior during the blowdown phase can be defined with fewer data points. The remainder of the comparisons are left to the reader's judgement and experience.

The LP data in Figures 7 and 8 show that it is possible to work with very complex data that are defined by a large number (12,500) of points at uniform time intervals. This requires a good method of smoothing for initial selection of the two key points, however, after that it is possible to work only with the original data and provide local correction for the position of the key points.

CONCLUSION

This report has demonstrated a powerful new method that can be used to aid in the evaluation and comparison of ballistic pressure data. The method provides an initial delay time, a characteristic time, and a peak pressure measure. These are useful parameters for the evaluation of ballistic data.

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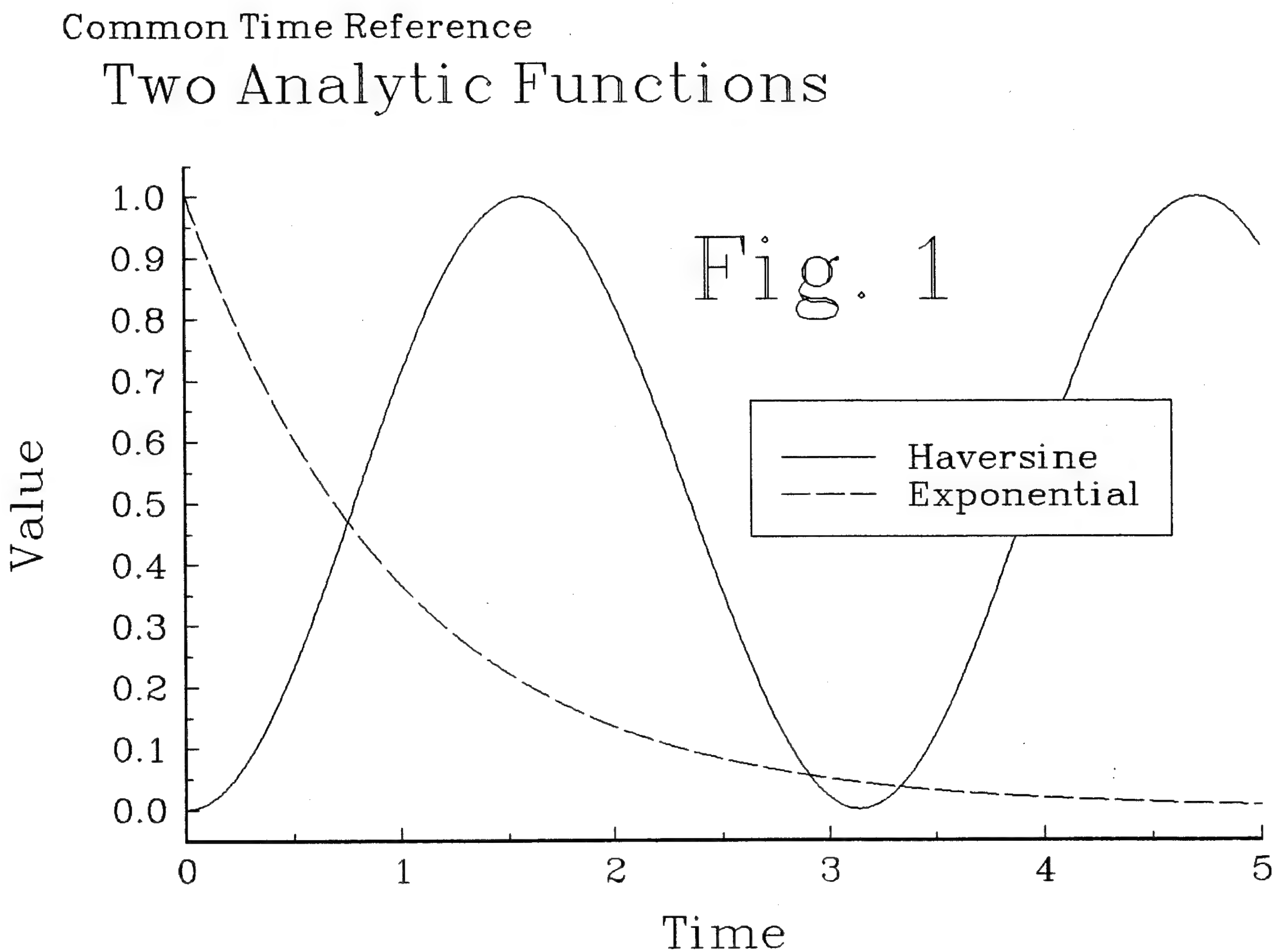

Common Time Reference
Two Analytic Functions
Value
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
Time
Haversine
Exponential

Fig. 1

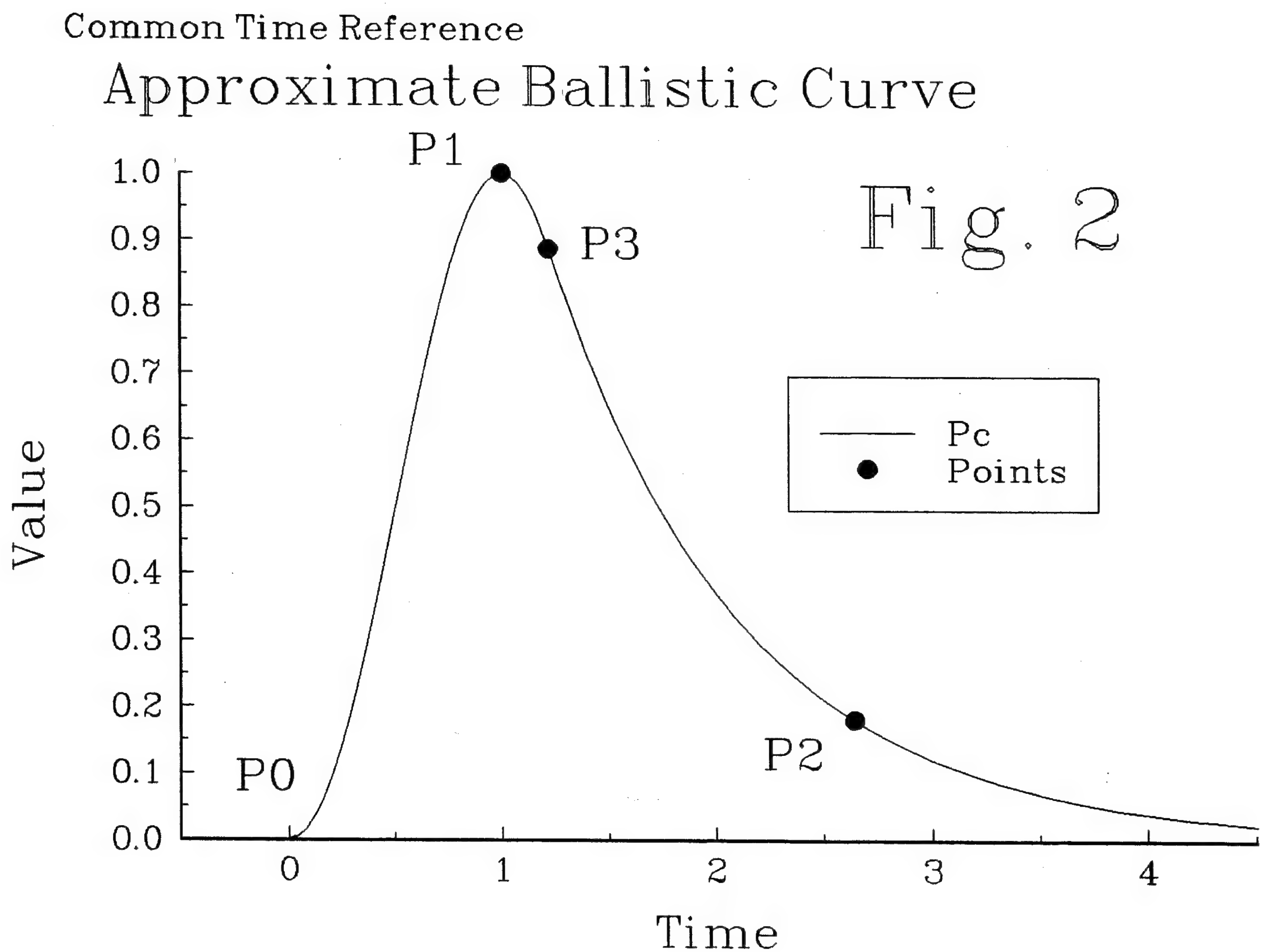

Common Time Reference
Approximate Ballistic Curve
P1
P3
P0
P2
Pc
Points
Value
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
Time

Fig. 2

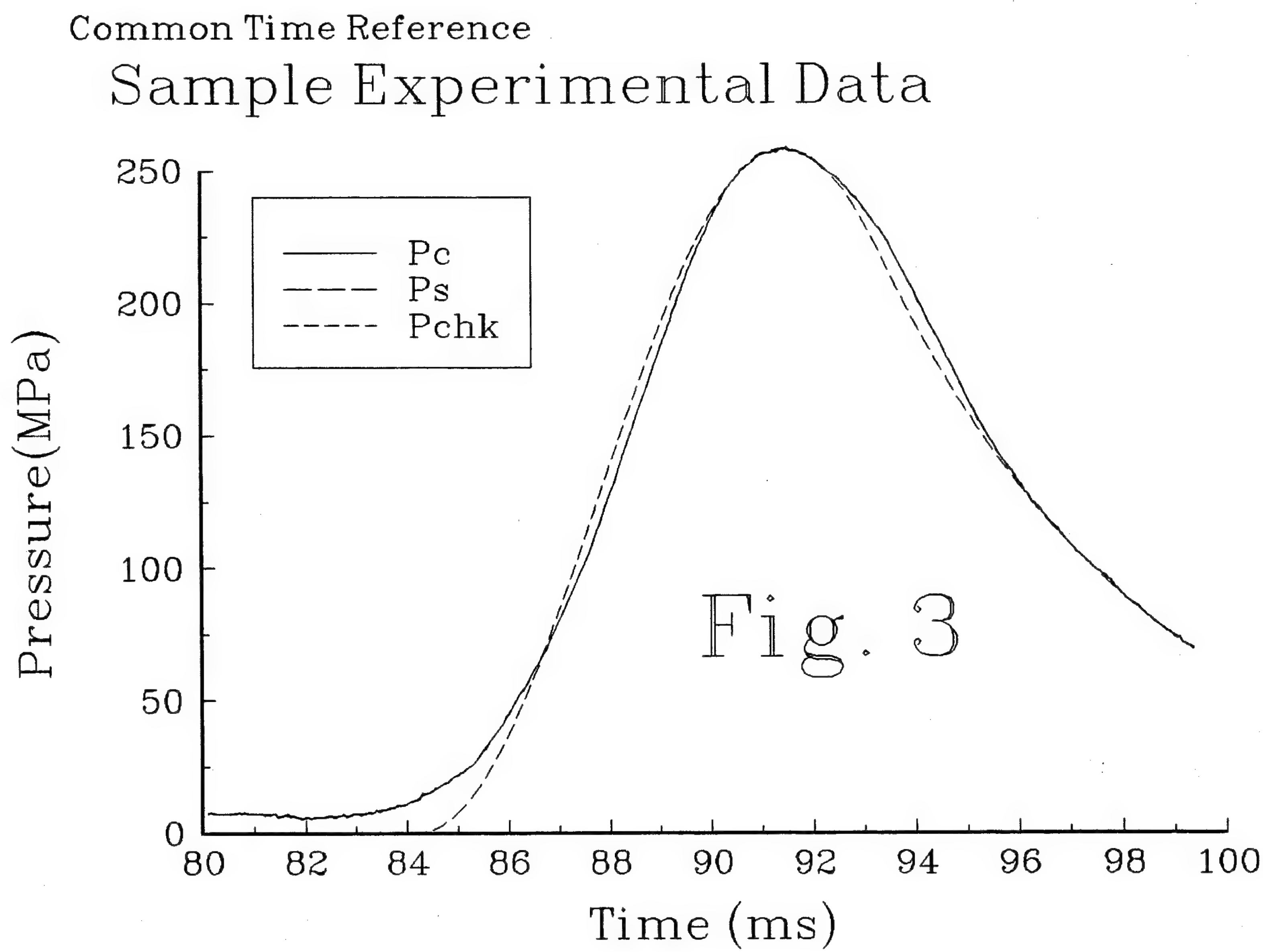
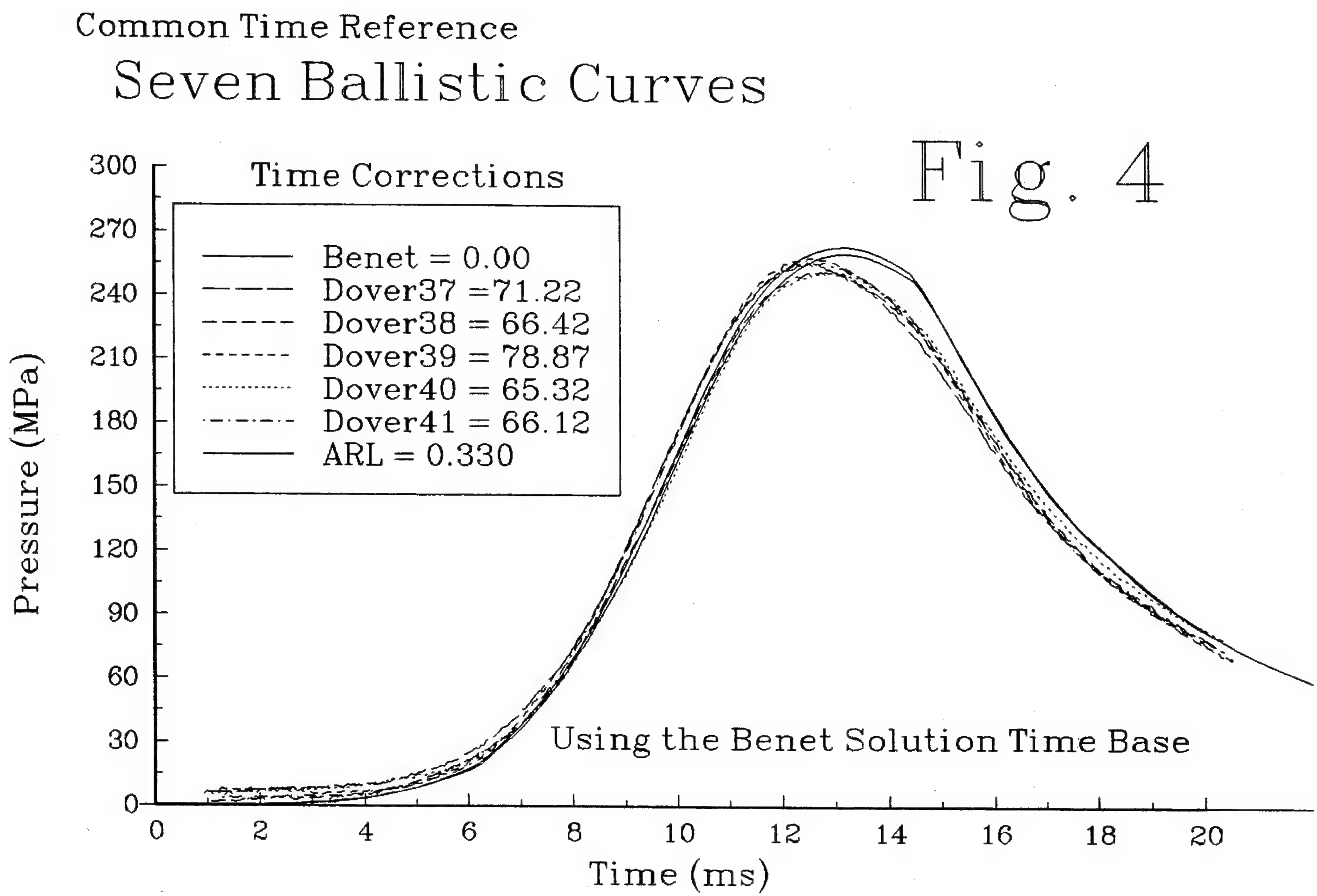

Common Time Reference
Sample Experimental Data
Pressure(MPa)
Time (ms)
Pc
Ps
Pchk
0
50
100
150
200
250
80
82
84
86
88
90
92
94
96
98
100

Fig. 3



Common Time Reference
Seven Ballistic Curves
Time Corrections
Benet = 0.00
Dover37 =71.22
Dover38 = 66.42
Dover39 = 78.87
Dover40 = 65.32
Dover41 = 66.12
ARL = 0.330
Pressure (MPa)
Time (ms)
Using the Benet Solution Time Base

Fig. 4

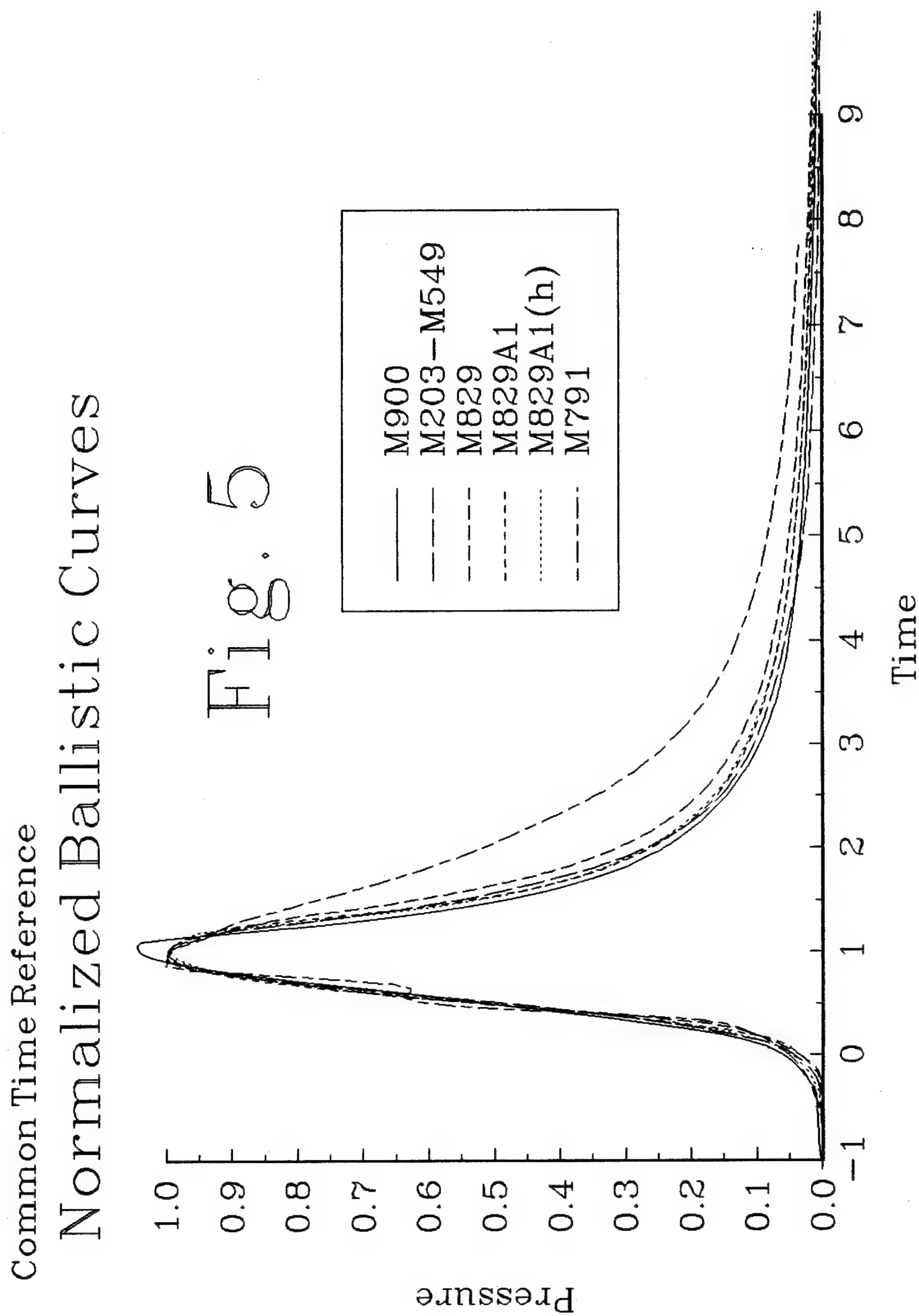
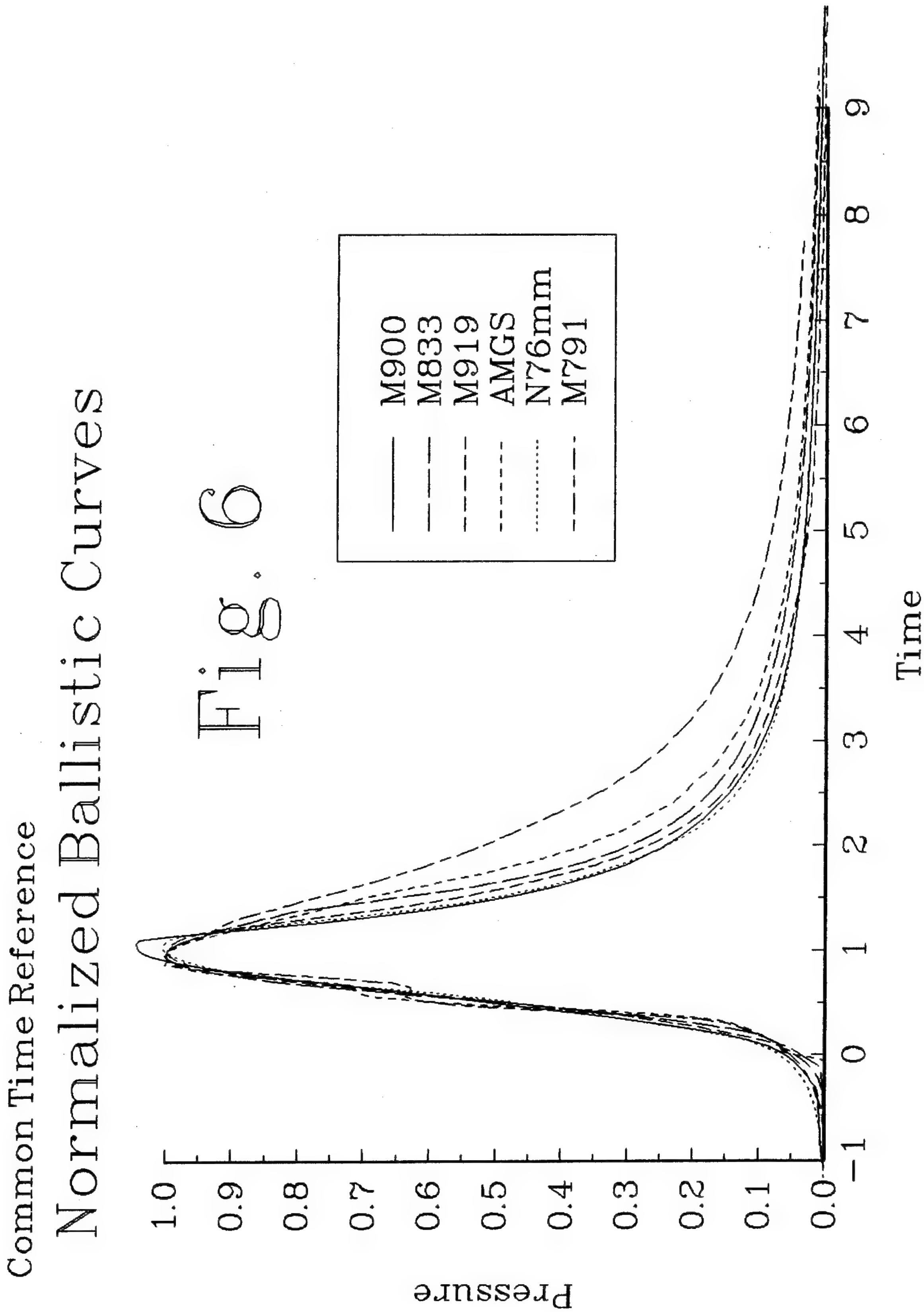

Common Time Reference
Normalized Ballistic Curves
Pressure
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-1
0
1
2
3
4
5
6
7
8
9
Time
M900
M203—M549
M829
M829A1
M829A1(h)
M791

Fig. 5


Common Time Reference
Normalized Ballistic Curves
Fig. 6
M900
M833
M919
AMGS
N76mm
M791
Pressure
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−1
0
1
2
3
4
5
6
7
8
9
Time

Common Time Reference

LP Gun Pressure

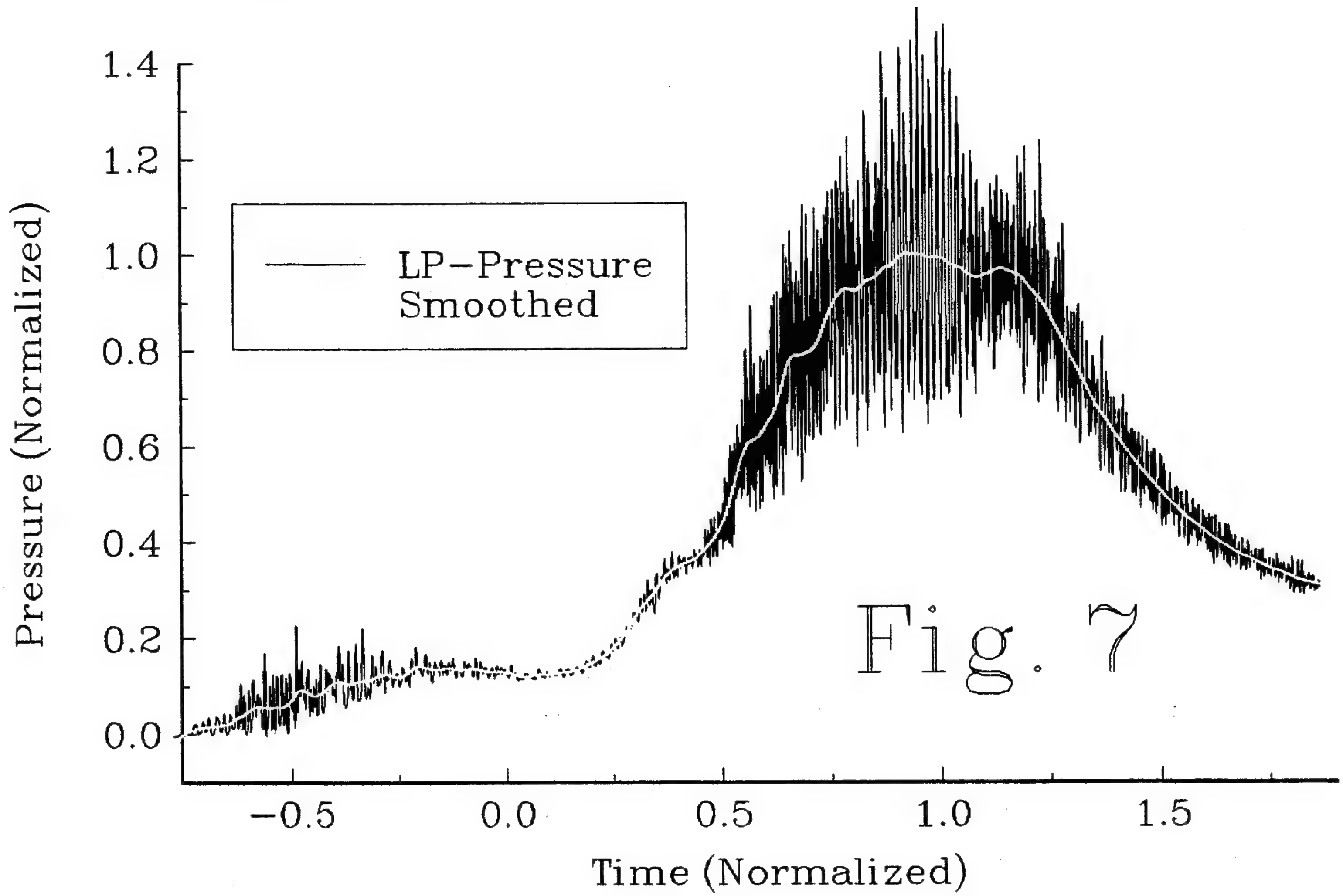
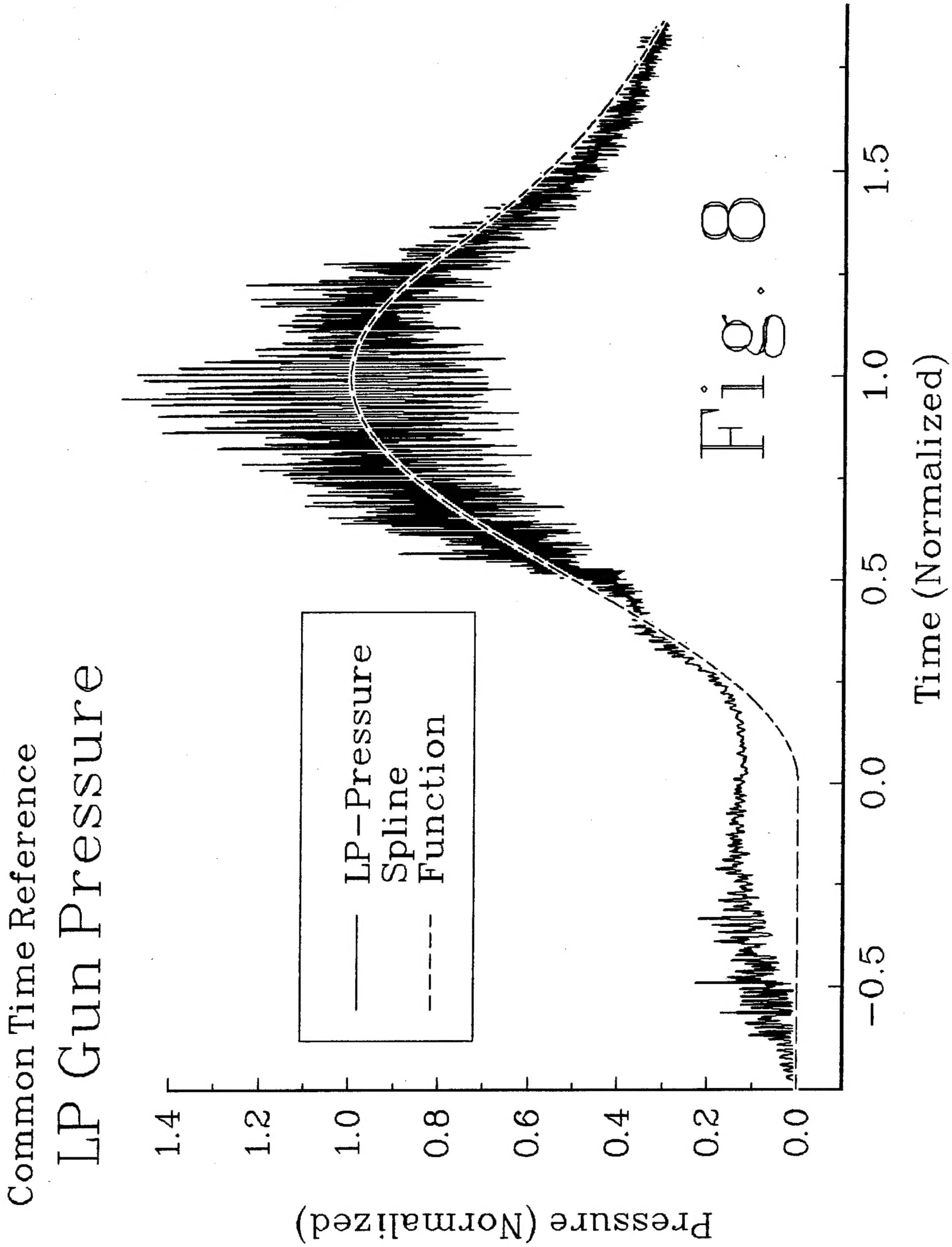


Fig. 7


Common Time Reference
LP Gun Pressure
LP-Pressure
Spline
Function
Pressure (Normalized)
Time (Normalized)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.5
0.0
0.5
1.0
1.5
Fig. 8

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